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ON THE POSSIBILITIES FOR THERMAL NEUTRON IMAGE INTENSIFICATION

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Harold Berger

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ABSTRACT

Possible techniques and materials for a thermal neutron image intensifier are compared. A vacuum-tube type intensifier, in which an electron image is accelerated and demagnified within an evacuated envelope, appears to present a useful possibility for a neutron image intensifier. Neutron scintillators for use in such an intensifier are compared, and it is concluded that a lithium-containing phosphor, enriched in Li-6, could be used to provide an intensifier useful for thermal neutron intensities of 10^5 n/cm^2-sec or higher. It is shown that such an intensifier would be capable of neutron image detection in the presence of an appreciable gamma-radiation background.

I. INTRODUCTION

The increased use of neutron radiographic inspection methods in recent years in inspection areas involving heavy materials,(1) reactor-control materials,(2) radioactive materials,(3) as well as others,(4,5) has renewed interest in the possibility of a neutron image intensifier. Although the value of such image converters was recognized long ago(6) as a result of the early investigations of neutron radiography,(7,8,9) the author is unaware of any recent activity in neutron image intensification. This report, outlining the results of some experimental efforts in this area and containing some suggestions for useful materials for a neutron image intensifier, is meant to provide some direction for the development of a useful neutron image intensifier.

Although the term, neutron image converter, could be taken to mean any technique that converts a neutron image into some other kind of signal and would therefore include radiography, spark counters,(4,10) fluoroscopic methods,(11) as well as others, the use of the term here implies sufficient image amplification so that some sort of immediate visible image can be readily observed. Several such techniques have been suggested and used in the field of X-ray image intensification. Following the classification system used in the recent paper by Niklas,(12) these systems include electronic, solid-state, and vacuum-tube methods.

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The electronic methods convert the X-ray image into an electronic signal, which is then displayed by television methods. The television image presentation is basic to the electronic image-intensification technique, as outlined in Niklas's review. Examples of this technique are the Image Orthicon pickup from a fluorescent X-ray screen[13] and the direct pickup of the signal in an X-ray sensitive vidicon.[14]

The solid-state systems include the solid-state amplifier combinations of photoconductive and electroluminescent layers,[15] and the system employing field-enhanced photoluminescence.[16]

The vacuum-tube systems involve the conversion of the X-ray image into an electron image, all or partially within a vacuum envelope. The most widely used such system is the one normally called the X-ray image intensifier,[17] a vacuum tube in which the X-ray image is converted to light, to photoelectrons, and then to an intensified visible image. This amplified visible image can be viewed directly, or by means of mirror, optical, or television methods.

In the X-ray field, the vacuum-tube type of image intensifier has received the greatest application use and has been developed to a relatively high degree. For this reason alone, the consideration of this type of intensifier for neutrons appears attractive. In addition, such use would involve a method for converting the neutron image into an electron image, either directly[18,19] or through an intermediate, light-emissive step. Fortunately, the method of neutron detection involving conversion from neutrons to light[11,20-22] has received considerable attention.

It is primarily this approach to neutron intensification that is considered in this report. Other possibilities would involve a material exhibiting a photoconductive type of neutron response for use in a neutron-sensitive vidicon, or a solid-state type of device. Studies of both CdS[23] and silicon p-n junctions[24] have shown some promise for solid-state neutron detection. However, neither of these detection techniques presently appears as far advanced as the scintillation type.

Therefore, the experimental study described in this report will be concerned primarily with material possibilities for a neutron image intensifier employing an electron image within an evacuated envelope. Intensification is provided by the voltage accelerating the electrons toward the phosphor output end of the intensifier, and by demagnification of the image. The primary change in design between the proposed neutron image intensifier and available X-ray image intensifiers is that provision must be made for suitable materials to yield an electron image of the incident neutron beam.

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II. EXPERIMENTAL DATA

A. Initial Tests

As an initial step, a commercially available X-ray image intensifier[a] was placed in a neutron beam to determine what, if any, response could be obtained. No noticeable response was obtained when the intensifier was used in a total neutron intensity[25] of 4.5 x 10^7 n/cm^2-sec.[b] This was true using the intensifier directly in the neutron beam, or using a neutron conversion screen (cadmium and gadolinium were used) against the outside of the face plate of the tube. The conversion screens emit prompt radiation (mostly gamma radiation) upon neturon bombardment, and it was felt that the emitted gamma radiation might stimulate the input phosphor. However, when a complete image intensifier tube was used, distance was a problem, since the glass face plate and some additional internal spacing separated the input phosphor screen and the conversion screen. Viewing of the output phosphor during this test was accomplished with a closed-circuit television system employing a vidicon pickup tube.

As a further check on the lack of response, a phosphor input screen[c] from a similar X-ray image intensifier was viewed with a photomultiplier tube, as shown in Figure 1. The graphs in the upper portion of Figure 1 show the photomultiplier tube current obtained with the phosphor screen alone, and with various types and thicknesses of converter screens that are in the neutron beam and in contact with the back surface of the phosphor screen.[d]

The highest photomultiplier tube current obtained was approximately 92 microamperes under the test conditions used. Values approaching this result for a cadmium converter screen 500 microns in thickness were found for 250-micron rhodium and 50-micron gadolinium converter screens. In the case of rhodium, which becomes radioactive with a half-life of 4.4 min, the decay of the light from the screen could be observed after the neutron beam port was closed.

Subsequent tests with the same arrangement in the light-tight box indicated that this level of photocurrent could be obtained by stimulating the phosphor with heavily filtered, 80-kVp X-radiation, having an intensity of about 50 mR/min.

(a) A 22-cm, X-ray image intensifier, the Rauland R-6175-RP, was used for this test.

(b) The neutron beam facility is described in Reference 25. The total neutron intensity used was 4.5 x 10^7 n/cm^2-sec, the cadmium ratio was 2.4, and the gamma intensity in the neutron beam was 110 R/hr.

(c) The screen used was an input phosphor screen from a Rauland X-ray intensifier, type R-6189-P.

(d) The phosphor screen was deposited on an aluminum substrate, which was then etched away, except for a thin aluminum backing.

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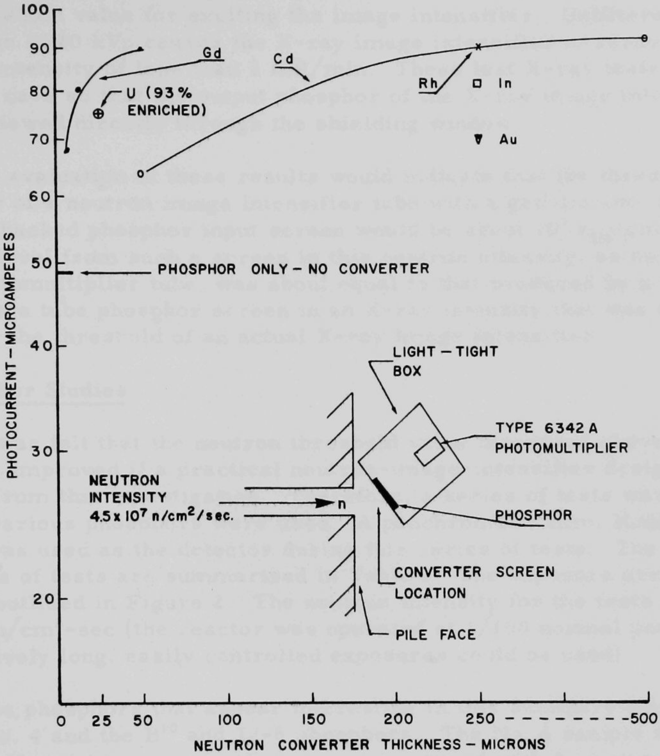


Fig. 1. Photomultiplier-tube Response for Various Neutron-exposed Intensifier Screen-phosphor Combinations.

The upper portion of the figure shows the photomultiplier-tube response obtained when an X-ray image-intensifier phosphor (phosphor number 1, Table I) was stimulated in a neutron beam having a total neutron intensity of 4.5×10^7 n/cm^2-sec, cadmium ratio 2.4, and gamma intensity 110 R/hr. Also shown is the response when the phosphor was backed with various thicknesses and types of neutron-converting screens. The lower portion shows the test arrangement used. The light-tight box was angled with respect to the neutron beam to place the photomultiplier tube outside the major beam area.

A further test with the X-ray image-intensifier tube indicated that this X-ray intensity, based on X-radiation of similar quality, was about the lower threshold value for exciting the image intensifier. Unfiltered X-radiation of 40 kVp causes the X-ray image intensifier to respond to an X-ray intensity of less than 2 mR/min. These last X-ray tests were made in a cave so that the output phosphor of the X-ray image intensifier could be viewed directly through the shielding window.

An evaluation of these results would indicate that the threshold sensitivity of a neutron image intensifier tube with a gadolinium- or cadmium-backed phosphor input screen would be about 10^7 n_{th}/cm^2-sec. The light level from such a screen in this neutron intensity, as measured by the photomultiplier tube, was about equal to that produced by a useful X-ray image tube phosphor screen in an X-ray intensity that was shown to be near the threshold of an actual X-ray image intensifier.

B. Phosphor Studies

It was felt that the neutron threshold value discussed above would have to be improved if a practical neutron-image-intensifier design were to result from this investigation. Therefore, a series of tests was initiated in which various phosphors were used. A panchromatic film, Kodak Super XX, was used as the detector during this series of tests. The data for this series of tests are summarized in Table I. The exposure arrangements used are outlined in Figure 2. The neutron intensity for the tests was 4.5×10^5 n/cm^2-sec (the reactor was operated at 1/100 normal power, so that relatively long, easily controlled exposures could be used).

The phosphors that appear interesting in this summary are those marked No. 4 and the B^{10} and Li-6 phosphors. The No. 4 sample was a full-sized X-ray image intensifier screen prepared with four parts ZnCdS(Ag) phosphor and one part LiF by weight. The LiF was 39% enriched with Li-6. The light output of this screen, measured in a standard quality-control test by the Rauland Corporation, was such that it would have been usable in an X-ray image intensifier. The B^{10} sample is described in Table I. The Li-6 phosphor, also described in Table I, has been optimized for back-screen film response, as far as lithium content is concerned.(11) It has been estimated that, for front-screen response, the optimum thickness of the Li-6 phosphor for light output will be in the order of 0.5 mm.

Table I

SUMMARY OF PHOSPHOR-FILM TESTS

Phosphor[a]	Physical Form[b]	Exposure[c] Method	Intensifier No. 1	Intensifier No. 2	Film[d] Density
No. 1	Chip, 0.25 mm	A	0	0	0.16
No. 1	Chip, 0.25 mm	A	0.5 mm Cd	0	0.19
No. 1	Chip, 0.25 mm	B	0.5 mm Cd	0	0.19
No. 1	Chip, 0.25 mm	A	0.5 mm Pb	0.5 mm Cd	0.28
No. 1	Chip, 0.25 mm	A	0.5 mm Pb	0.05 mm Gd	0.26
No. 2	Chip, 0.375 mm	A	0.5 mm Cd	0	0.31
No. 2	Chip, 0.375 mm	A	0.5 mm Pb	0.5 mm Cd	0.29
No. 2	Chip, 0.375 mm	A	0.05 mm Gd	0	0.30
No. 2	Chip, 0.375 mm	A	0.5 mm Pb	0.05 mm Gd	0.29
No. 3	Powder, single layer	A*	0	0	Background
No. 3	Powder, single layer	A*	0.05 mm Gd	0	0.24
No. 3	Powder, single layer	A*	0.5 mm Pb	0.05 mm Gd	0.24
No. 3A	Powder, single layer	A*	0	0	Background
No. 3B	Powder, single layer	A*	0	0	Background
No. 4	Chip, 0.5 mm	A	0	0	1.33
B^{10}, ZnS(Ag)	Sheet, 0.3 mm	A	0	0	0.56
B^{10}, ZnS(Ag)	Sheet, 0.3 mm	B	0	0	0.75
Li-6F, ZnS(Ag)	Chip, 1 mm	A	0	0	1.32
Li-6F, ZnS(Ag)	Chip, 1 mm	B	0	0	1.32
Li-6F, ZnS(Ag)	Chip, 1 mm	A	0.5 mm Cd	0	0.42
Li-6F, ZnS(Ag)	Chip, 1 mm	B	0.05 mm Gd	0	0.66
Li-6F, ZnS(Ag)	Powder, single layer	A*	0	0	0.62

[a]Phosphors were as follows:

No. 1. ZnCdS(Ag) phosphor screen from Rauland Image Intensifier, Type R-6189-P. Phosphor was deposited in a resin binder.

No. 2. A screen similar to No. 1, but thicker.

No. 3. ZnCdS(Ag) powder (furnished by the Rauland Corp.).

No. 3A. No. 3 plus 1% (by weight) gadolinium oxide powder.

No. 3B. No. 3 plus 3% (by weight) gadolinium oxide powder.

No. 4. A special screen made using ZnCdS(Ag) phosphor (No. 3), plus 25% by weight Li-6F (39% enriched), in a resin binder.

B^{10}, ZnS(Ag). A flat, rectangular scintillator, a boron polyester type containing ZnS(Ag). The boron was 92% enriched in B^{10}. The active thickness was 0.3 mm. The scintillator has a plastic backing 3 mm thick.

Li-6F, ZnS(Ag). An ANL-prepared phosphor containing one part Li-6F (92% enriched) and four parts ZnS(Ag) by weight.

[b]Single-layer thicknesses were obtained by placing Scotch tape on the powder and using the layer of phosphor that remained on the tape.

[c]The letters refer to the exposure methods shown in Figure 2. The A* techniques were all Scotch-tape techniques for obtaining the single layer of phosphor. These were Type A exposures. In all cases, the tape was between the phosphor and the film emulsion.

[d]Films were developed in batches with control films to be sure that development was identical. Since neutron exposure of all samples was also identical (100 sec at 4.5×10^5 n/cm^2-sec), film density is a representation of the relative light output from the various phosphors, for the same neutron exposure.

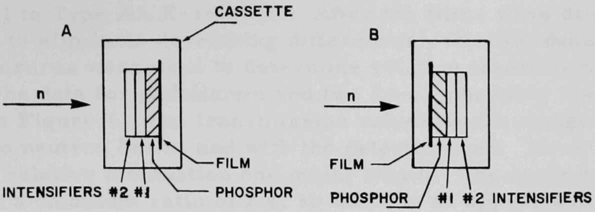


Fig. 2. Neutron Exposure Arrangements Used in Film Tests of Phosphor Materials and Converter Screens

C. Metal Screens

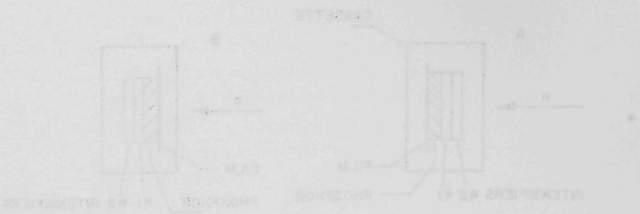
Since gadolinium is known to emit electrons (internal-conversion electrons of approximately 70 keV energy) upon neutron bombardment,(18) some comparison tests were made to determine the number of electrons emitted per incident neutron. Film techniques based on Kodak Lantern Slide Plates-Medium were used, and neutron exposures for various thicknesses of gadolinium screens were compared with electron exposures (by an electron microscope). The neutron exposures were all made by the use of exposure arrangement A, as shown in Figure 2, with the phosphor replaced by a gadolinium screen. The results are shown in Figure 3.

Use of these thin emulsion plates, which would be expected to show negligible response to the gamma radiation also emitted by the gadolinium screen, resulted in an optimum thickness of about 12.5 microns for the gadolinium converter screen. For a thicker, X-ray film emulsion, the gadolinium thickness that yields the best film density for identical neutron exposures is appreciably greater,(26) since more gamma radiation is detected. It may therefore be assumed that most of the film exposure in this case is due to electrons from the gadolinium.

The best film density obtained on the neutron exposures compares with an electron exposure of about 7 x 10^8 electrons/cm^2, made by exposing similar plates in a Siemens (Elmiskop I) electron microscope. All the plates were developed together. Since the neutron exposure to yield the same film density was about 10 times as great, the data would indicate that a gadolinium screen with a thickness of 12.5 microns will yield approximately one electron for every 10 thermal neutrons striking the tube. These electrons are emitted on the side opposite the incident neutron beam.

D. Absorption Data

The neutron attenuation of the promising materials used in this study was obtained by placing various thicknesses of the material in the neutron beam, activating an indium foil by exposing it to the neutron beam after passing through the materials under test, and then exposing the



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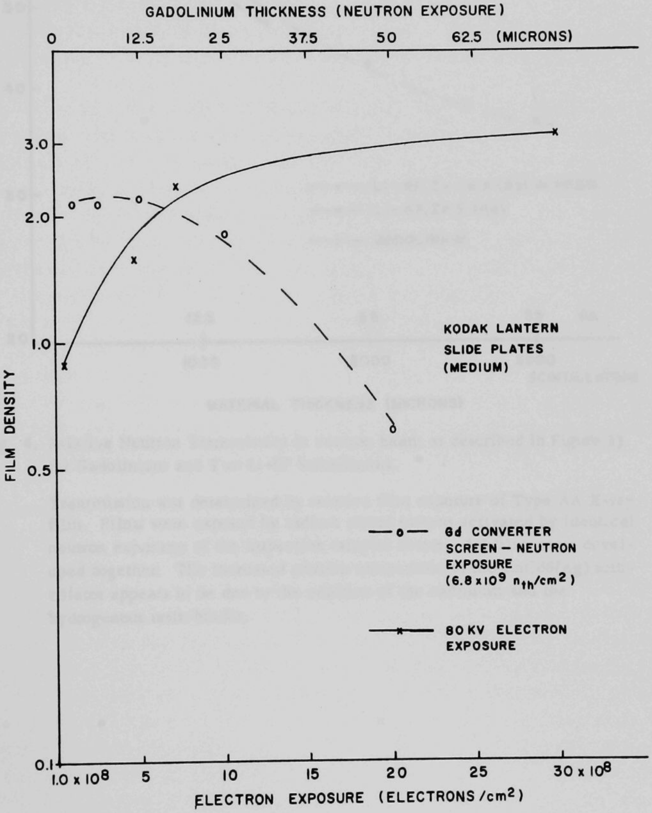

Fig. 3. Comparison of Electron-exposed and Neutron-exposed Photographic Plates.

Film density is plotted against gadolinium thickness for the same neutron exposure (dashed line) when neutron exposure is by arrangement A in Figure 2. The solid curve shows the density-versus-electron exposure of similar plates. All plates were developed together. Similar plate densities were obtained for a total thermal-neutron exposure of 6.8 x 10^9 n/cm^2 (for the 12.5-micron gadolinium screen) and for a total electron exposure of about 7 x 10^8 electrons/cm^2.

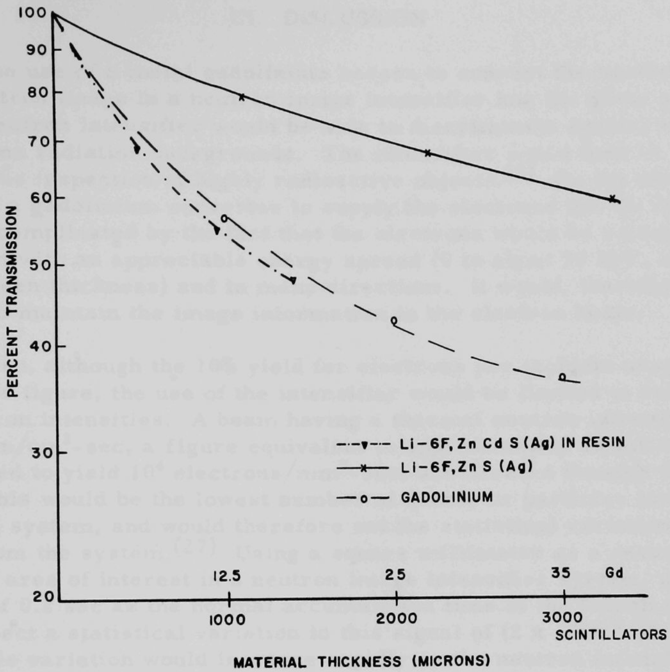

Fig. 4. Relative Neutron Transmission (a neutron beam as described in Figure 1) for Gadolinium and Two Li-6F Scintillators.

Transmission was determined by relative film exposure of Type AA X-ray film. Films were exposed by indium metal screens activated by identical neutron exposures of the inspection samples shown. All films were developed together. The increased neutron attenuation of the ZnCdS(Ag) scintillator appears to be due to the addition of the cadmium and the hydrogenous resin binder.

III. DISCUSSION

The use of a metal gadolinium screen to convert the neutron beam to an electron image in a neutron image intensifier has the great attraction that the neutron intensifier would be able to discriminate against very high gamma radiation backgrounds. The intensifier would then be useful even for the inspection of highly radioactive objects.(3) On the debit side, the use of a gadolinium converter to supply the electrons for the intensifier would be complicated by the fact that the electrons would be emerging from the screen with an appreciable energy spread (0 to about 70 keV, because of the screen thickness) and in many directions. It would, therefore, be difficult to maintain the image information in the electron beam.

Also, although the 10% yield for electrons per incident neutron is a reasonable figure, the use of the intensifier would be limited to relatively high neutron intensities. A beam having a thermal neutron intensity of about 10^7 n/cm^2-sec, a figure equivalent to approximately 10 mR/sec, would be expected to yield 10^4 electrons/mm^2-sec, accelerated through the intensifier. This would be the lowest number of quanta or particles involved in the image system, and would therefore set the statistical variation one would expect from the system.(27) Using a square millimeter as a reasonable minimum area of interest in a neutron image intensifier system, and using a figure of 0.2 sec as the normal accumulation time of the human eye, one would expect a statistical variation in this signal of $(2 \times 10^3)^{1/2}/(2 \times 10^3)$ or 2.2%. This variation would increase rapidly as the neutron intensity reaching the intensifier decreased in value and would contribute to increasing difficulty in recognizing lower contrast detail in the image.

Fortunately, a much improved result appears possible through the use of a scintillator input screen in a neutron image intensifier. Figure 4 indicated that a Li-6F, ZnCdS(Ag) screen, 0.5 mm thick, will transmit about 70% of an incident-reactor neutron beam. Although part of the beam attenuation in this case does not contribute to light emission from the screen (neutron scattering by the hydrogenous resin binder in the screen, for example), it may be reasonable to assume that approximately 30% of the incident thermal neutron beam intensity could contribute to useful alpha and light emission because of the increased attenuation achievable by using a material more highly enriched in Li-6. If the 30% figure is assumed to be correct, the low point in the scintillator system, the neutrons absorbed in the scintillator, would be 3×10^6 n_{th}/cm^2-sec, or 6×10^3 n/mm^2 for a period of 0.2 sec. The statistical variation in this case, therefore, would be $(6 \times 10^3)^{1/2}/(6 \times 10^3)$ or 1.3%.

The scintillator would appear to provide a useful response for appreciably lower neutron intensities. A comparison of film exposures from the data in Table I shows that the lithium scintillators yield approximately 80 times more light for a given neutron exposure, as compared with a

III. DISCUSSION

The use of a metal gadolinium screen to convert the neutron beam to an electron image in a neutron image intensifier has the great attraction that the neutron intensifier would be able to discriminate against very high gamma radiation backgrounds. The intensifier would then be useful even for the inspection of highly radioactive objects. On the debit side, the use of a gadolinium converter to supply the electrons for the intensifier would be complicated by the fact that the electrons would be emerging from the screen with an appreciable energy spread (0 to about 70 keV, because of the screen thickness) and in many directions. It would, therefore, be difficult to maintain the image information in the electron beam.

Also, although the 10% yield for electrons per incident neutron is a reasonable figure, the use of the intensifier would be limited to relatively high neutron intensities. A beam having a thermal neutron intensity of about 10^7 n/cm^2-sec, a figure equivalent to approximately 10 mR/sec, would be expected to yield 10^5 electrons/mm^2-sec, accelerated through the intensifier. This would be the lowest number of quanta or particles involved in the image system, and would therefore set the statistical variation one would expect from the system.[4,7] Using a square millimeter as a reasonable minimum area of interest in a neutron image intensifier system, and using a figure of 0.2 sec as the normal accumulation time of the human eye, one would expect a statistical variation in this signal of $(2 \times 10^5)^{1/2}/(2 \times 10^5)$ or 2.2%. This variation would increase rapidly as the neutron intensity reaching the intensifier decreased in value and would contribute to increasing difficulty in recognizing lower contrast detail in the image.

Fortunately, a much improved result appears possible through the use of a scintillator input screen in a neutron image intensifier. Figure 4 indicated that a Li-6F, ZnCdS(Ag) screen, 0.5 mm thick, will transmit about 70% of an incident-reactor neutron beam. Although part of the beam attenuation in this case does not contribute to light emission from the screen (neutron scattering by the hydrogenous resin binder in the screen, for example), it may be reasonable to assume that approximately 30% of the incident thermal neutron beam intensity could contribute to useful alpha and light emission because of the increased attenuation achievable by using a material more highly enriched in Li-6. If the 30% figure is assumed to be correct, the low point in the scintillator system, the neutrons absorbed in the scintillator, would be 3×10^6 n_a/cm^2-sec, or 6×10^4 n/mm^2 for a period of 0.2 sec. The statistical variation in this case, therefore, would be $(6 \times 10^4)^{1/2}/(6 \times 10^4)$ or 4.1%.

The scintillator would appear to provide a useful response for appreciably lower neutron intensities. A comparison of film exposures from the data in Table I shows that the lithium scintillator's yield approximately 80 times more light for a given neutron exposure, as compared with a cadmium- or gadolinium-backed phosphor of the type normally used for an X-ray image intensifier. If reciprocity-law failure response of the film[28] is considered, a better comparison of the relative light outputs between these two materials can be made by keeping other variables constant and varying neutron intensity until the film responses are equal. Through this approach, and through varying reactor power to change neutron intensity, the intensity factor became about 100 times. Therefore, one would expect that the lithium scintillator used as an input screen in a neutron image intensifer would provide a threshold response at about $10^5\ n_{th}/cm^2$-sec.

Note that the statistical variation produced with the scintillator system could be much reduced by increasing the absorbing power of the scintillator, for example by increasing thickness. Attempts to improve the absorption and the light output of the scintillator, by backing the material with combinations of cadmium, gadolinium, and lead were relatively unsuccessful, as indicated in Table I. The idea was that the gamma emission from the cadmium or gadolinium would help stimulate the phosphor, either directly, or by photoelectron emission from an intervening lead screen. However, the test result indicated that decreased, rather than increased, light output was obtained, at least with the screen thicknesses tried.

In terms of gamma response, it has been shown[4,29] that scintillators of this type yield a light output for an exposure to 1 mR of cobalt-60 gamma radiation approximately equal to the light produced by a thermal neutron exposure of $10^4\ n/cm^2$. These data, however, were taken with film techniques based on the use of thick scintillators (approx 2 mm) as back screens. Using thinner phosphor screens, as in an image intensifier, one would anticipate even less gamma response.

This was somewhat confirmed in tests with the Rauland R-6175-RP X-ray image intensifer. With this unit installed in a cave, the output screen was observed while a highly radioactive, irradiated reactor-fuel capsule was maneuvered near the input screen end of the tube. The capsule could be moved as close as 2.5 cm to the face plate of the intensifier before a noticeable brightening of the output screen was observed. The radiation intensity at the face plate with this setting was approximately 5,000 R/hr, all relatively hard gamma radiation.

The high-energy gamma response of the image intensifier was sufficiently low that the capsule could even be shadowed by an X-ray beam, while it was essentially in contact with the face plate of the intensifier. Figure 5 shows a photograph of the output phosphor of the image intensifier under those conditions. The X-ray beam used was 110 kVp, 4 mA, approximately 40 cm distance. This was the maximum voltage available from the X-ray generator used, and the capsule was not penetrated at that setting.

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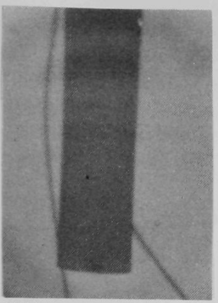

39496

Fig. 5

Photograph of Portion of Output Screen of an X-ray Image Intensifier.

The X-ray beam is shadowing (but not penetrating) a highly radioactive, irradiated, reactor fuel capsule. Estimated gamma intensity at the image intensifier face plate due to the capsule was about 30,000 R/hr. The wire visible in a portion of the image was attached to the capsule. The picture was made while the capsule was being held by a manipulator in a cave. The photograph was made through the cave window.

IV. CONCLUSIONS

A neutron image intensifier of the vacuum-tube type, employing a neutron-light-photoelectron type of intensifier input, appears feasible when used with existing techniques and materials. A tube of this nature, in which a Li-6 enriched lithium-phosphor combination would provide the initial neutron image detection, would probably take the form shown in Figure 6, essentially a cross-section view of an available vacuum-tube type X-ray image intensifier, except for the detecting phosphor material. Such a tube now appears to be capable of responding to thermal neutron intensities in the order of 10^5 n/cm^2-sec or higher. Therefore, one would anticipate a very useful image presentation, if an imaging system of this type were used in a typical, nuclear reactor, neutron radiography facility, having a thermal neutron intensity in the 10^6 to 10^8 n/cm^2-sec range. The fact that the intensifier might also display relatively little gamma response broadens the possible applications of the imaging system.

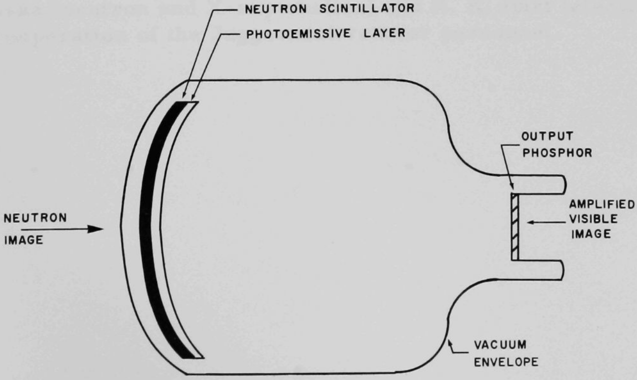

Fig. 6. Cross-section View of a Proposed Neutron Image-intensifier Tube

In addition to the neutron intensifier, a complete neutron imaging system would include some means either of providing shielding for an observer located near the output of the intensifier or for bringing the intensified visible image out of the radiation area. A closed-circuit television system and/or a mirror system could be used to satisfy this last requirement.

The availability of such an imaging system would appreciably expand the usefulness of the neutron inspection method. In addition to providing images at minimal radiation levels and thereby improving the possibility that neutron images might be useful in biological problems,(5,30) the industrial application to inspection objects subjected to varying conditions would also be very useful. Postirradiation annealing studies of experimental reactor fuel materials present an example of these latter application areas.(31)

Further developmental efforts on a neutron image intensifier system are recommended.

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